The Theory of Relativistic Jet Formation in Galactic Sources: Towards a Unified Model

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Abstract. I review recent progress in the theory of relativistic jet production. The presently favored mechanism is an electrodynamic one, in which charged plasma is accelerated by electric fields that are generated by a rotating magnetic field. The most pressing issues of current interest are understanding what factors control the jet power, its speed, and its degree of collimation, and how these properties determine the type of jet observed and its effect on its environment.
Recent observations of microquasars, pulsars, gamma-ray bursts (GRBs) and core-collapse supernovae indicate that jets play an important, and in some cases possibly dominant, role in each of these. The presence of a jet in all cases may provide an important clue to how these sources may be related. Based on these observations, and on recent theoretical investigations, I propose an evolutionary scheme that attempts to unify all of these relativistic galactic jet sources. I also discuss several important issues that must be resolved before this (or another scheme) can be adopted.

1. Introduction: An Expanded Definition of "Microquasar"

The standard definition of "microquasar" — the object that is the subject of this meeting — is a binary black hole candidate X-ray source that possesses a relativistic jet at least part of the time in its life cycle. For the purpose of this talk, and to illustrate the unified model proposed, I will use an expanded definition of microquasar, stated as follows. A microquasar is any galactic, stellar-mass source that produces a jet whose velocity is a significant fraction ($> 10\%$) of the speed of light c. This definition includes the following sources:

1. Classical microquasars (GRS 1915+105, GRO J1655-40, GX 339-4, etc.): These produce jets with $v_{jet} > 0.6 - 0.95c$ ($\Gamma_{jet} \equiv [1 - v_{jet}^2/c^2]^{-1/2} > 1.25 - 3$).
2. Gamma-ray bursts (GRBs): Believed to be "microquasars in formation" and produce jets with $\Gamma_{jet} \sim 100 - 300$ that point toward us.
3. SS433-type objects: Observed properties suggest a super-Eddington accreting, magnetized neutron star. Jets have speed $v_{jet} \sim 0.25c$.
4. Isolated pulsars (Crab, Vela, etc.): Jets now have been detected by Chandra in these objects and have speeds $v_{jet} \sim 0.5c$.
5. Core-collapse supernovae: There is growing evidence that supernovae also produce jets with a power comparable to the explosion itself. Expected speeds are $v_{jet} \sim 0.25 - 0.5c$ — the escape speed from the new proto-neutron star.

The inclusion of core-collapse supernovae (SN) above is the key to the unified model. In the mid 1990s it was discovered that such supernovae emit polarized light in the optical band [1, 2], caused by electron scattering by an asymmetrically-expanding explosion.

The variation of polarization properties with time and with different SN types gives important clues to its nature. In a given SN, the degree of polarization Π increases with time but the polarization direction remains constant in time and wavelength, indicating that the asymmetry is global and maintains a fixed direction. For Type IIa SN (ones with a large hydrogen-rich envelope), the $\Pi \sim 1\%$, indicating only a 2:1 or less asymmetry. For Type IIb SN (ones that have lost their hydrogen envelope prior to the explosion, leaving only the helium envelope), Π is higher ($\sim$2%), indicating a 2.5:1 axial ratio. For SN Type Ib/Ic (ones that have lost most or all of their envelope, leaving a compact blue Wolf-Rayet star that then explodes), Π is quite high ($4-7\%$), indicating a 3:1 axial ratio or better. Clearly, the deeper one sees into the explosion, the more elongated the exploding object appears. The observers have concluded that core-collapse SN have a global prolate shape that appears to be associated with the central engine producing the explosion. A jet, with energy comparable to that of the explosion itself, significantly alters the shape of the envelope, creating the elongated, polarized central source. In the paper below we will show that all five of the above "microquasars" are intimately related, both in the physical origins of the jet itself and in their astrophysical origins as well.

2. Basic Principles of Magnetohydrodynamic Jet Production

The basic principles of MHD jet production have been described elsewhere [3]. The reader is referred to that paper for a more detailed description, and more comprehensive figures, than in the short review given below.

2.1. *The Jet Engine Itself: Launching of the Jet Outflow*

2.1.1. *Jet Production in Accreting Systems and Pulsars*

Several mechanisms for producing bipolar outflows have been suggested (explosions in the center of a rotationally-flattened cloud, radiation-pressure-driven outflows from a disk, etc.), but none of these is able to produce outflows approaching the highly-relativistic speeds observed in the fastest jet sources. The currently-favored mechanism is a magnetohydrodynamic one, somewhat similar to terrestrial accelerators of particle beams. Indeed, electromagnetic acceleration of relativistic pulsar winds has been a leading model for these objects since the 1960s. MHD (or electrodynamic) jet production was first suggested in 1976 [4, 5] and has been applied model to rotating black holes [6] (BZ) and to magnetized accretion disks [7] (BP). This mechanism has now been simulated [8, 9, 10] and is sometimes called the "sweeping pinch" mechanism.

The most important ingredient in the MHD mechanism is a magnetic field that is anchored in a rotating object and extends to large distances where the rotational speed of the field is considerably slower. Plasma trapped in the magnetic field lines is subject to the Lorentz ($J \times B$) force, which, under conditions of high conductivity (the MHD assumption), splits into two vector components: a magnetic pressure gradient ($-\nabla B^2/8\pi$) and a magnetic tension ($B \cdot \nabla B/4\pi$). Differential rotation between the inner and outer regions winds up the field, creating a strong toroidal component (B_ϕ in cylindrical [R, Z, ϕ] coordinates). The magnetic pressure gradient up the rotation axis ($-dB_\phi^2/dZ$) accelerates plasma up and out of the system while the magnetic tension or "hoop" stress ($-B_\phi^2/R$) pinches and collimates the outflow into a jet along the rotation axis.

This basic configuration of differential rotation and twisted magnetic field accelerating a collimated wind can be achieved in all objects identified in Sect. 1. For classical microquasars and GRBs, the field will be anchored in the accreting plasma, which may lie in a rotating disk (BP) and/or may be trapped in the rotating spacetime of the spinning central black hole itself (BZ). In the case of SS433-type objects, isolated pulsars,

and core-collapse SN the rotating field is anchored in the pulsar (or proto-pulsar). In SS433 and core-collapse SN the source of the accelerated plasma is, once again, accretion, but in isolated pulsars it is believed to be particles created in spark gaps by the high (10^{12} G) field.

2.1.2. *The Case of Kerr Black Holes: Direct and Indirect Magnetic Coupling*

The jet-production mechanism envisioned by BZ generally involved direct magnetic coupling of the accelerated plasma to the rotating horizon. That is, magnetic field lines thread the horizon, and angular momentum is transferred along those field lines to the external plasma via magnetic tension. However, another, indirect, coupling is possible. This mechanism, suggested by [11] (PC) and recently simulated by us [12], has the same effect as the BZ mechanism (extraction of angular momentum from the rotating black hole by the magnetic field), but the field lines do not have to thread the horizon itself. Instead, they are anchored in the accreting plasma. When this plasma sinks into the ergosphere near the black hole ($R < 2\ GM/c^2$), frame dragging causes the plasma to rotate with respect to the exterior, twisting up the field lines in a manner similar to the situation when the field is anchored in a disk or pulsar. (This occurs even if the accreting plasma has no angular momentum with respect to the rotating spacetime.) The twisted field lines then have two effects:

1. Electromagnetic power is ejected along the rotation axis in the form of a torsional Alfven wave. Eventually the output Poynting flux power should be dissipated in the production and acceleration of particles and a fast jet.
2. The back-reaction of the magnetic field accelerates the ergospheric plasma (in which it is anchored) to relativistic speeds *against* the rotation of the black hole. The counter-rotating ergospheric plasma now formally has negative angular momentum and negative energy (negative mass); that is, it has given up more than its rest mass in energy to the external environment. It is on orbits that must intersect the black hole horizon, and, when it does, the mass of the black hole decreases by a value equal to that negative energy.

This process is the magnetic equivalent of the Penrose process, but instead of extracting black hole rotational energy by particle scattering, the energy is extracted by scattering of an Alfven wave off the ergospheric plasma particles. Determining whether the BZ or PC process occurs in certain systems is an important question for future study.

2.1.3. *Output Engine Power: Thick Accretion Flows Make Better Jets*

The output Poynting flux power of the rotating magnetic field depends on the strength of the poloidal component of the field $B_{p0} = (B_{R0}^2 + B_{Z0}^2)^{1/2}$, its angular speed Ω_0, and the size of the rotating region R_0. In the non-relativistic magnetized disk theory of BP the jet power is given by

$$L_{jet} = B_{p0}^2 R_0^3 \Omega_0 \tag{1}$$

In the relativistic theory of rotating black holes (BZ) the output power is

$$L_{jet} = f B_{p0}^2 R_0^4 \Omega_0^2 / (4c) \tag{2}$$

The geometric factor f is of order unity in BZ and in several early papers that use these formulae; however, others [13] have argued for a value $f \sim 1/8$, which reduces the estimated power by almost an order of magnitude. Eq. (2) occurs in a variety of relativistic cases, not just in BZ. PC's jets are the equivalent of the BP disk process, but in a black hole ergosphere; they also find an output power with a similar form and $f \sim 1$. A similar expression is obtained for pulsar winds if one takes the output power to be

$L_{jet} = \Gamma_{jet}\dot{M}_{jet}c^2$, where $\dot{M}_{jet}$ is the mass outflow rate, and uses the general pulsar result that $\Gamma_{jet} \approx \sigma \equiv B_{p0}^2 R_0^4 \Omega_0^2/(4\dot{M}_{jet}c^3)$ [14], the magnetization parameter. Eq. (2), therefore, generally is used to estimate the power in relativistic cases (most of those considered here), while eq. (1) is used in non-relativistic situations, such as jets from protostars or planetary nebulae.

Eq. (2) has interesting implications for the output power for accretion disks of various thicknesses. It has been argued [15] that the poloidal magnetic field in an accretion disk is only a fraction of the azimuthal field: $B_{p0} \sim (H_0/R_0)B_{\phi 0}$, where H_0 is the disk half-height at radius R_0 and $B_{\phi 0}$ is the azimuthal field that is responsible for the angular momentum transport in the accretion disk at R_0. Substituting into eq. (2) we obtain

$$L_{jet} = f H_0^2 B_{\phi 0}^2 R_0^2 \Omega_0^2/(4c) \tag{3}$$

Therefore, thick accretion flows with $H_0 \sim R_0$, such as ADAFs, are expected to have much more powerful jets than thin accretion flows and $H_0 << R_0$, such as standard accretion disks. We have used this property [16] to explain the observed presence of jets in the microquasar low/hard state and the absence of jets in the high/soft state [17]. Recent numerical results [18] which perform 3-dimensional global simulations of the magneto-rotational instability, show a jet being launched, but only from the inner portion of the accretion disk where the flow is geometrically thick and the poloidal magnetic field is substantial.

2.2. *Formation of the Jet: Acceleration and Collimation*

2.2.1. *Slow Acceleration and Collimation is Probably the Norm*

Because the dynamical time scale is of order 0.1 ms or less in these objects, a steady state is set up fairly quickly in jet ejection events that last even only a few seconds. In a steady state, the wind accelerates as it expands vertically away from the rotator. A jet is not fully formed until its speed exceeds the local wave propagation speed, *i.e.*, the total Alfven speed $V_A = [(B_R^2 + B_Z^2 + B_\phi^2)/(4\pi\rho)]^{1/2}$, where ρ is the mass density in the outflowing material. The place where this occurs, often called the Alfven point or Alfven surface, generally is well above the rotating object producing the accelerating torsional Alfven wave. Analytic [7, 19] and numerical [20] studies of this steady state show that the outflow is rather broad at the base, and it slowly focuses as it is accelerated. At a height $Z_A > 10R_0$ above the disk, the total Alfven speed is exceeded, the flow is focused into a narrow cylindrical or conical flow, and little more acceleration and collimation takes place. The terminal jet speed v_{jet} is of order $V_A(Z_A)$, and this speed is usually of order the escape speed from the central rotator $V_{esc}(R_0)$.

There now is observational evidence that, in at least some *extragalactic* systems, the steady-state picture of slow acceleration and collimation is correct. Very high resolution VLBA radio images of the M87 jet [21] show a broad opening angle at the base that narrows to only a few degrees after a few hundred Schwarzschild radii. In addition, it has been argued [22] that most quasar jets must be broad at the base: they lack soft, Comptonized and relativistically-boosted X-ray emission that would be expected from a narrow, relativistic jet flow near the black hole. For microquasars, a similar result still would imply a collimation region much too small to resolve with current telescopes — $100r_S \sim 10^8$ cm or 2 nano-arcseconds at a distance of 3 kpc.

2.2.2. *Rapid Acceleration and Collimation May be Possible for Strong Fields*

We have found that when the MHD luminosity of the jet exceeds a critical value

$$L_{crit} = E_{escape}/\tau_{free-fall} = 4\pi\rho_0 R_0^2 (GM/R_0)^{3/2} \tag{4}$$

rapid acceleration of the plasma can take place [23]. In this case, magnetic forces will exceed gravitational and centrifugal forces and the field will dynamically pinch the plasma above the rotator. Angular momentum conservation will cause this pinched material to spin very rapidly, and if this material then re-connects to the rotator below, strong shear in the re-connected region will create an even stronger toroidal magnetic field that rapidly accelerates and collimates the outflow. The resulting jet is very fast, possibly significantly exceeding the escape speed $V_{esc}(R_0)$, and highly-collimated within a few R_0. We have called this process the "magnetic switch", because it sets in abruptly when $L_{jet} > L_{crit}$. Such strong acceleration and collimation near the rotator should occur only in very special cases when the field is dynamically dominant and rapidly rotating (*e.g.*, in corona above an accretion disk or rapidly-spinning neutron star or black hole).

2.3. *Attaining Relativistic Speeds: Strong Magnetic Fields Far from the Central Engine*

Some of the microquasar phenomena listed in Sect. 1 achieve very fast jet speeds. Technically, these do not exceed the escape speed from the surface of a black hole ($v_{jet} = c$), but in practice they seem far too large to be explained by the simple MHD wind model discussed in Sect. 2.2.1. How, then, are highly-relativistic speeds attained? It is unlikely that the magnetic switch process can explain them. Not only should this process be rather rare, but observational evidence discussed in Sect. 2.2.1 rules out the magnetic switch as the explanation for the high Γ_{jet} seen in M87 and in many quasars: those jets seem too broad at their bases to be rapidly accelerated close to the black hole. By analogy, we probably also should look for another explanation in classical microquasars and GRBs.

One possible model is that of long, straight magnetic fields that dominate the jet dynamics. The argument is as follows. In order to attain relativistic speeds we need a relativistic Alfven speed, or

$$\Gamma_A = V_A/c = B/(4\pi\rho c^2)^{1/2} >> 1 \tag{5}$$

Either B must be strong inside the jet or "mass-loading" of the magnetic field lines must be low. These requirements present their own problems. Any magnetic field carried with the flow has an effective mass density of $\rho_m \sim B_\perp^2/8\pi c^2$, where $B_\perp$ is the component of the field that is perpendicular to the jet flow vector. If $B_\perp \sim B$, then substitution of ρ_m into eq. (5) shows that Γ_A never will be able to attain a value much greater than unity. One solution to this problem is to keep the magnetic field well-ordered and straight over long distances and primarily parallel to the jet flow, so that $B_\perp << B$. The jet flow then slips along the parallel magnetic component, which does not contribute to the plasma inertia, only occasionally accelerated further by the oscillating and rotating transverse component $B_\perp$. The acceleration can continue until $\Gamma_{jet} > \Gamma_A$.

Semi-analytic models of such "Poynting-flux-dominated" jets have been built [19, 24]. However, no numerical simulations of these highly relativistic jets have been performed yet. The best numerical results so far are from *non*-relativistic simulations [10, 25], which compute a jet loaded with a decreasing density (increasing V_A) material. In this non-relativistic simulation, the field pitch angle is not so small, so $B_\perp \sim B_\parallel$. But, the important point is that the flow is stable, even over long distances. The torsional Alfven wave is able to transport energy and further accelerate the flow far from its origin.

3. MHD Jet-Powered Supernovae: Microquasars Buried inside Stars

Several authors have suggested in the past that MHD phenomena may power supernovae [26, 27]. The recent discovery that SN ejecta are elongated by an asymmetric jet-like flow has stimulated renewed interest in these models and, in particular, in the possibility

that an MHD jet produced by the proto-pulsar may be the source of the explosion energy in all core-collapse SN. We have proposed [28] an explosion mechanism that is consistent with the above properties of MHD jets. The jet is produced in the iron mantle, just outside the proto-neutron star. An object with a 10^{15} G field and a rotation period of ~ 1 ms can produce a jet power of $\sim 3 \times 10^{51}$erg s^{-1} and a total energy of $\sim 3 \times 10^{52}$ erg — more than enough to eject the outer envelope and account for the observed explosion energy. The proto-neutron star spins down to more respectable rotation periods (> 10 ms) in about ~ 10 seconds. (The model is similar to that of Ostriker & Gunn [29], with their 10^{12} G pulsar fields replaced by 10^{15} G proto-pulsar fields.) The jet outflow is composed of iron-rich material and is initially broad at the base. It therefore can couple well to the outer envelope and eject it. The flow then collimates at large distances ($> 10^{7-8}$ cm) from the core, forming a bipolar outflow that imparts an elongated shape to the ejecta.

This model also includes a gamma-ray burst trigger. In very rare instances, the field can be dynamically strong ($B > 10^{16}$ G), leading to satisfaction of the magnetic switch condition (eq. 4). The jet then becomes narrow and very fast, coupling poorly to the mantle, punching through the outer envelope [30], escaping the star, and producing a heavy iron "lobe" outside it, traveling at a speed of 0.05-0.3 c. The explosion therefore fails, and much of the mantle falls back onto the proto-neutron star, putting the system into a state very similar to that at the beginning the "failed SN" GRB model [31]. When the mantle fallback accretes enough material onto the proto-neutron star (after several minutes to hours), the neutron star is crushed to a black hole, and a new very fast ($\Gamma_{jet} >> 1$) jet is produced via the BZ or PC mechanisms discussed above. The relativistic jet catches up with the slow, iron-rich lobe at a distance of $d \sim v_{jet}\tau_{fallback} \sim 10^{12-13}$ cm, and the interaction of jet and lobe produces gamma-rays, optical afterglow, and an iron-rich spectrum.

4. Towards a Unified Model for All Galactic Relativistic Jet Sources

The possible unification of SN and GRBs, as being different possible outcomes in the final stages of the death of a massive star and both caused by MHD-powered jets, strongly suggests a unifying evolutionary sequence for all galactic sources with relativistic jets. The model is shown in Figure 1, and includes all objects discussed in Sect. 1. The sequence begins with a progenitor massive star that is about to undergo core collapse. Most collapse to a neutron star, ejecting a broad MHD jet in the process that drives the SN explosion and produces the observed asymmetry. After the envelope dissipates, if the pulsar is an isolated object, residual rotation of the magnetized remnant still drives an MHD outflow and a relativistic jet like that seen in the Crab and Vela pulsars. If the pulsar resides in a binary system, it may accrete material from its companion star in a super-Eddington phase ($\dot{M}_{acc} >> 10^{18}$g s^{-1}) and appear like SS433 for a brief time. Cessation of the accretion, angular momentum evolution of the pulsar, and possible collapse to a black hole all could serve to alter SS433's present state.

In rare circumstances, the MHD SN jet will fail to eject the envelope, or perhaps the progenitor core will collapse directly to form a black hole. In either case a GRB event is generated in a manner similar to that in the failed SN model. The GRB jet event will not spin down the black hole completely (although a significant amount of rotational energy may be extracted from the black hole by another means — gravitational waves). After the envelope dissipates, if the black hole is an isolated object, it will emit little radiation and be difficult to detect. On the other hand, if the newly-formed hole is in a binary system, it also can accrete plasma and field from its companion, thereby producing a strong jet and classical microquasar. Again, changes in the accretion rate and angular momentum evolution of the black hole will alter the microquasar's observational state. Many old

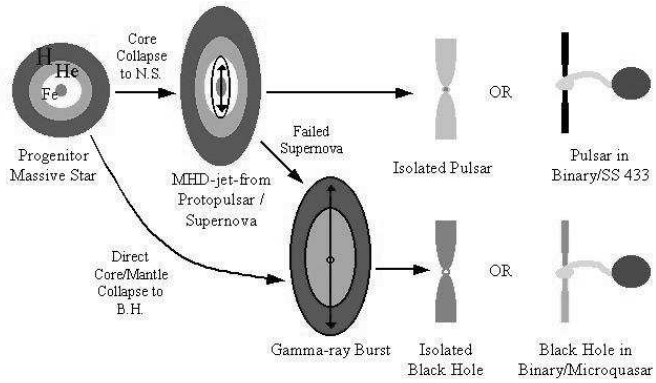

Figure 1. The proposed unified model for galactic relativistic jet sources.

microquasars may have masses and angular momenta quite different from those they possessed when first formed.

The key element of this unified model is that the final evolutionary outcome of a massive star core is ultimately determined by the magnitude and direction of that star core's angular momentum and magnetic field. We therefore should consider the jets seen in young pulsars and SS433-type objects to be vestiges of the mechanism that exploded the massive stars from which they came and, in a similar manner, consider the jets in microquasars to be the remnants of the gamma-ray burst that triggered the black hole's formation eons ago. Jets are the echoes of violent events of the distant past.

The 10^{14-15} G magnetic field strengths needed in SN cores are the real key to the success of the MHD SN model. Magnetars are believed to have surface field strengths of this order, but pulsars typically have fields of order 10^{12-13} G, which are too weak to produce the observed explosion power or energy. If stronger fields existed in pulsars at the time they were formed, they must have been dissipated either during the SN process or shortly thereafter, but it is not known how that dissipation may have taken place. Secondly, there also may be competing jet mechanisms (neutrino radiation pressure, etc.) which we have not discussed here. Thirdly, while we have suggested a possible SN failure mechanism (the magnetic switch), much more detailed theoretical work will be needed before we will be able to perform the simulations necessary to rule out different such mechanisms. Finally, there is a problem that needs to be addressed by all SN models. The iron mantle in the progenitor star is very neutron rich. If much of it is ejected (and the $1.4 M_\odot$ protoneutron star is left), then the predicted amount of *r*-process material may be much larger than that observed. It is a general problem for all core-collapse SN models to produce a neutron star remnant while still not over-producing the *r*-process elements.

The model also predicts that the formation of a "microblazars" [32] will appear as a GRB, along with possible mass sterilizations or extinctions on the earth if close enough [33, 34]. A very bright event may have left a permanent record on one hemisphere of the moon or on other natural satellites in the solar system.

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